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A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies – Part II: Results

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ABSTRACT

A clear consensus exists in German society that renewable energy resources have to play a dominant role in the future German energy supply system. However, many questions are still under discussion; for instance the relevance of the different technologies such as photovoltaic systems and wind energy converters installed offshore in the North Sea and the Baltic Sea. Concerns also exist about the cost of a future energy system mainly based on renewable energy. In the work presented here we tried to answer some of those questions. Guiding questions for this study were: (1) is it possible to meet the German energy demand with 100% renewable energy, considering the available technical potential of the main renewable energy resources? (2) what is the overall annual cost of such an energy system once it has been implemented? (3) what is the best combination of renewable energy converters, storage units, energy converters and energy-saving measures? In order to answer these questions, we carried out many simulation calculations using REMod-D, a model we developed for this purpose. This model is described in Part I of this publication. To date this model covers only part of the energy system, namely the electricity and heat sectors, which correspond to about 62% of Germany's current energy demand. The main findings of our work indicate that it is possible to meet the total electricity and heat demand (space heating, hot water) of the entire building sector with 100% renewable energy within the given technical limits. This is based on the assumption that the heat demand of the building sector is significantly reduced by at least 60% or more compared to today's demand. Another major result of our analysis shows that – once the transformation of the energy system has been completed – supplying electricity and heat only from renewables is no more expensive than the existing energy supply.

Contents

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1. Introduction

The current discussion on how or even whether we should transform our fossil-fuel based energy system to a renewable system is often based on emotions rather than facts. Political instruments like the German Act for Renewable Energy Technologies “Erneuerbare-Energien-Gesetz” (EEG) are very controversial. Discussions are carried out about the number or the kind of power plants needed, the dimensioning of storage and the expansion of the electricity or district heating grids. In this paper, we aim to assess these issues by drawing on numbers and assumptions from different reliable sources and applying a complex computer model that calculates hourly energy balances for the interaction between the German electricity and heat sectors. The assumptions and the methodology of our REMod-D model were introduced in the first part of this two-paper series [1]. In the present paper, we consider different scenarios in which the energy demand for space heating, hot water and electricity is satisfied with 100% renewable energy resources.[1] We investigate different system configurations, the influence of importing electricity on the system dimensioning, the consequence of keeping a certain proportion of fossil fuels in the system and the importance of energy retrofit measures in the building sector.

2. Constrained potential

The location of Germany inherently causes limitations on the production of electricity and heat from renewable energy sources. Due to limiting factors like required area, average wind velocity or available solar radiation intensity, the availability of renewable energy resources at any time is finite. What these limitations for Germany are and how they restrict the energy system will be discussed in the following paragraphs.

2.1. Wind turbines

To calculate the theoretical installable capacity of wind turbines in a certain country, both the availability and especially the useable area have to be evaluated. The number of wind turbines that can be built on this area depends on the separation needed between two turbines. This distance is necessary to guarantee good wind conditions for each turbine, so that the efficiency of converting wind into electricity is not affected. This theoretical potential is then reduced because of different social, environmental, economic or political restrictions. Due to the wide diversity of influences, we will mention only the most important ones (more factors are specified e.g. in [4]). Economic viability has the greatest influence on the decision as to whether a wind turbine should be built or not. If a turbine is installed in a location with little wind, such as in wind shadows or rough terrain, the efficiency decreases and the amount of produced electricity, and thus revenue, diminish. In addition, with increasing distance from the coast, the total cost of offshore wind turbines increases due to longer grid connection distances and especially due to higher expense for constructing turbines in deeper water.

Besides these technical restrictions, the so-called “soft factors” also strongly influence the potential of renewable energy technologies. For example, there are restrictions for offshore wind turbines such as the distance to the coast due to esthetic reasons, military areas, trade routes or environmental restrictions such as bird sanctuaries. Also laws that regulate the distance of turbines from housing areas can restrict the number of installed onshore wind turbines. Within this study, we use the constrained potential determined in the Windenergiereport Deutschland (2011) published by Fraunhofer IWES [5]. The values given are 200 GW_{el} and 85 GW_{el} for wind onshore and offshore, respectively.

2.2. Solar thermal collectors and photovoltaics

In a further study published by Fraunhofer IWES [6], the constrained potential of areas for solar thermal or photovoltaic facilities is calculated. These areas result from theoretically available areas that are reduced due to specific limiting factors. The economic viability is technically constrained mainly because of differences in the intensity of solar radiation. It is, for instance, not reasonable to install solar collectors on north-facing surfaces, be they roofs, railway embankments, highway sound barriers or facades. On open land, it is possible to choose the perfect orientation, but these areas are usually in high demand and competition exists with other forms of land usage such as agriculture or nature conservation areas. Fig. 2.1 shows the values obtained in the Fraunhofer IWES study. In total, there is a viably useful area of 2845 km² (excluding open land areas[2]), which is equivalent to an installed capacity of about 2000 GW_{th} of solar thermal collectors or an installed capacity of 400 GW_{el} of photovoltaic systems or, of course, a combination of both technologies.

2.3. Hydropower

In contrast to the technologies mentioned above, the installable potential for hydropower facilities in Germany is relatively small. Therefore this technology is not included within the optimization process of the model and the values are fixed (cf. [1]). The capacity of installed run-of-river installations is fixed at 5 GW_{el} and the amount of electricity generation is limited to 21 TWh. These values are slightly higher than today's values. In 2007, the installed capacity of run-of-river power plants in Germany was 4.3 GW_{el}

[1] In comparison, the energy supply for domestic heat and hot water in Germany in 2010 was mainly based on fossil fuels (oil 25%, natural gas 47%, coal 2%) and was based only to a small extent on renewable energy (12%), district heat (10%) and electricity (4%) [2]. The electricity production in 2010 was based on about 86% fossil fuels and nuclear power and the rest was based on renewable energy sources [3].

[2] We do not include the possible useful area of open space due to the great uncertainty concerning future use of these areas.

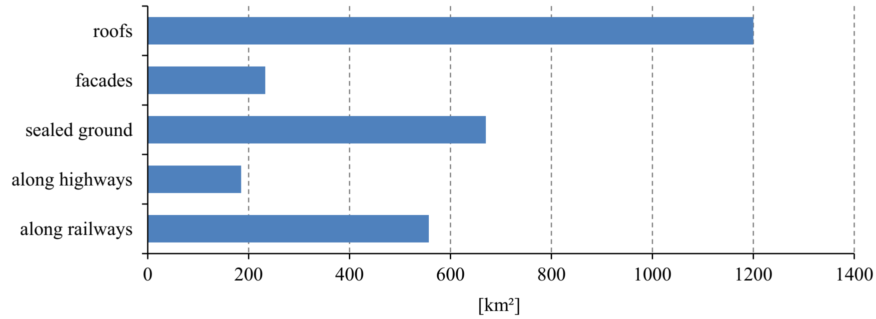

Fig. 2.1. Potentially available area for the installation of systems for conversion of solar energy in Germany (solar thermal or photovoltaic systems) (data from [6]).

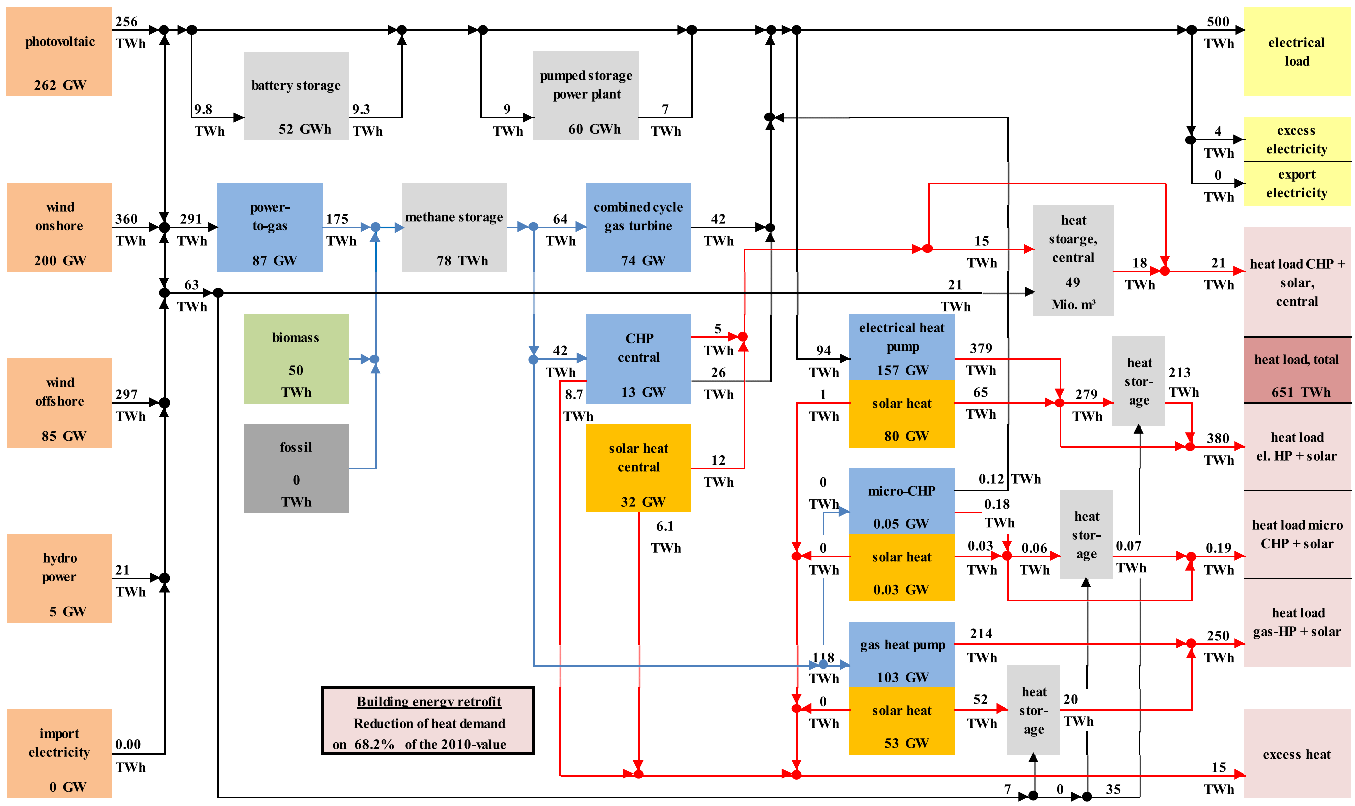

Fig. 3.1. "REMax" system with minimum total annual cost (black lines: electricity, blue lines: gas, and red lines: heat). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

[7]. The small estimated increase to 5 GW_{el} is mainly due to assumed repowering rather than new construction of facilities, because the technical potential is already almost fully utilized.

Today's value for installed capacity of pumped hydro-power reservoirs is 6.6 GW_{el} and the amount of storable energy is given as 40 GWh [7]. Since there are new reservoirs already in planning and since the potential is not yet completely utilized, we estimate the future grid capacity to be 10 GW_{el} and the total energy storage capacity to be about 60 GWh. Both values are fixed within our model-based calculations.

3. Results

In the following, we discuss the results of the simulations performed and scenarios analyzed.[3] We will show that there are different system constellations that lead to very similar total costs. Furthermore, we will discuss the variation of specific parameters to assess their influence on the total system structure. All assumptions, cost and technical values that are not mentioned in this paper are published in part I of this series of papers [1].

3.1. Systems with 100% renewable energy for electricity and heat

The cost-optimized system calculated with our tool is shown in Fig. 3.1 (named "REMax"). The annual cost to operate, maintain and rebuild the system is calculated to be around 111 billion €. Fig. 3.1 depicts the results for a 100% renewable energy system, in which the size of all facilities is calculated with our cost-optimization algorithm. The required installed capacity of each technology that generates, converts and exchanges electricity, gas or heat is illustrated in Fig. 3.1. The summarized energy output and input over the period of one year is also shown. In addition, the implementation degree of energy-saving retrofit measures is part of the optimization process and is calculated in this system to 68.2% of the 2010 value for Germany. At this stage of our model it is not possible to assess the specific influence of energy retrofits for different types of buildings such as single homes, medium-density housing or commercially used buildings.

[3] A detailed description of the methodology of this model can be found in [1].

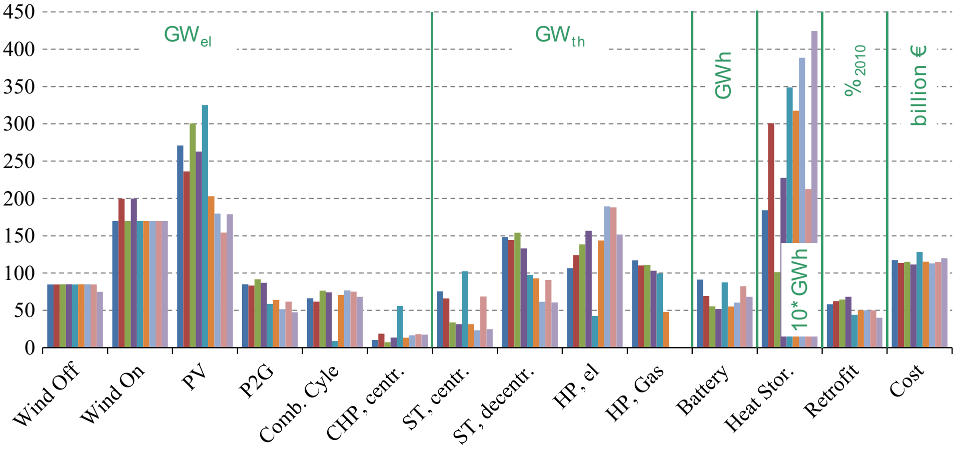

Fig. 3.2. Installed capacity of main components for different system compositions that lead to total annual cost in a range from 111 to 120 billion € per year (off=offshore; on=onshore; PV=photovoltaic; P2G=power-to-gas; CHP=combined heat and power; ST=solar thermal; and HP=heat pump).

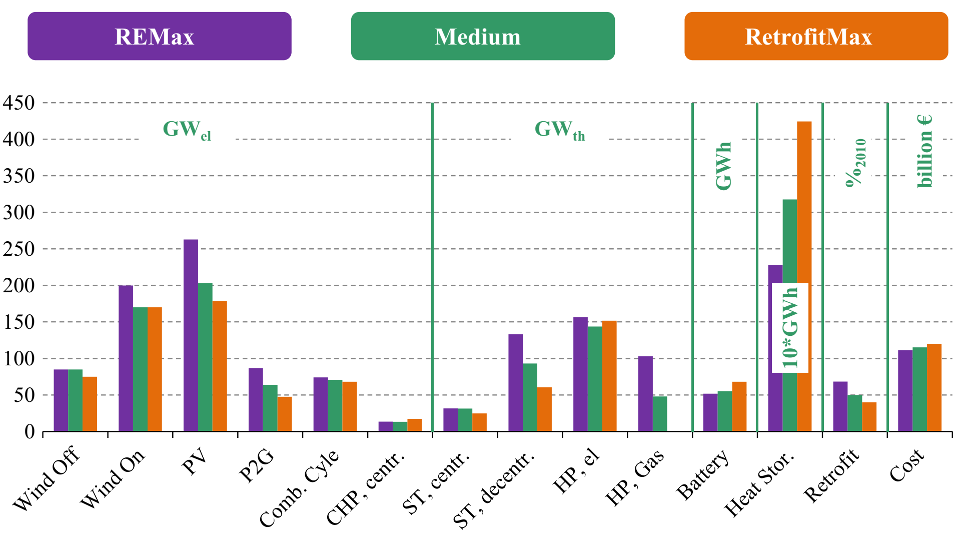

Fig. 3.3. Installed capacity of main components for three selected systems (off=offshore; on=onshore; PV=photovoltaic; P2G=power-to-gas; CHP=combined heat and power; ST=solar thermal; and HP=heat pump).

This number is assumed to be an average value for the total energy savings based on the space-heating demand of 2010 (780 TWh, cf. [1]). It is also not yet possible to determine the optimal degree of energy-saving measures depending on the type of building. The next development step of the model will analyze these questions, so that it will be possible to assess the cost effectiveness of energy-saving building retrofit as a function of building type.

Our simulation results show that different system constellations lead to slightly higher, but very similar, total system costs compared to the results shown in Fig. 3.1. Fig. 3.2 shows the results of different random scenarios to illustrate the variety of possible system configurations with rather similar annual total cost values. It can be seen that the range of total system cost is only from 111 to 120 billion €, whereas the system composition changes significantly.

To analyze the system behavior in more detail, three systems (c.f. Fig. 3.3) having nearly similar cost are chosen. It can be seen that even though the total system costs are quite similar, the technical composition differs significantly. This behavior leaves a margin to consider different influences other than technical restrictions and illustrates the flexibility of the system composition in the optimization process.

The systems shown in Fig. 3.3 are examples for system configurations that lead to comparable total cost but have different characteristics concerning the technology dimensioning and the extent of energy-saving building retrofit.

These systems can be distinguished as follows:

3.1.1. REMax system

This system is obtained by completely free optimization. This means that the contribution from each technology that is subject to optimization is calculated within the algorithm introduced in [1]. It should be noted that the capacities for onshore and offshore wind are at their potential limits (85 GW_{el} wind offshore and 200 GW_{el} wind onshore, cf. Section 2). The amount of installed photovoltaic capacity, however, does not reach its limit but still achieves a large installed capacity (262 GW_{el}). Particularly the large number of installed photovoltaic systems and onshore and offshore wind facilities leads, depending on the actual weather conditions, to an oversupply of electric energy during many hours of the year. To make use of this oversupply, the energy storage and conversion facilities are correspondingly large. The installed capacity of power-to-gas facilities for instance reaches values of around 87 GW_{el}. This sizing makes it possible to accommodate most of the electricity generation peaks and thus to store most of the surplus electricity in renewable gas. This high value of renewable gas-producing facilities leads again to a large amount of usable energy

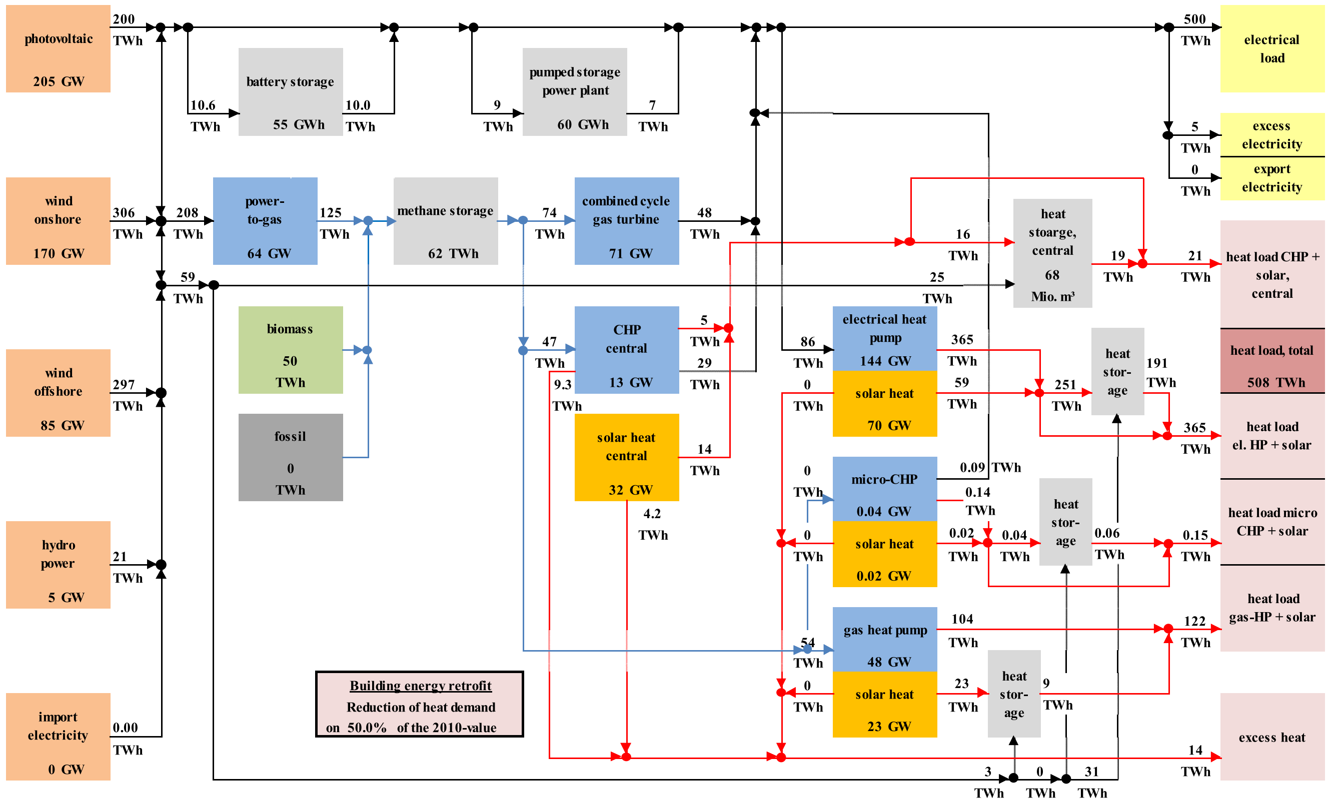

Fig. 3.4. "Medium" system.

for the heating sector. Hence the installed capacity of gas-driven heat pumps is high. The high availability of energy (electricity, synthetic gas) leads to a comparatively low reduction of the energy demand for heating of buildings to 68.2% of the 2010 value. Although this system was identified as the cost-optimal configuration, it is debatable whether this system presents a reasonable structure for a future energy supply. The very large numbers of installed photovoltaic and wind converters as well as electricity-converting systems like power-to-gas facilities make this system rather difficult to implement. For onshore and offshore wind, the technical potential would be fully exploited. One way to reduce the installed capacities of renewable electricity or gas-producing facilities is to reduce the energy demand in the heating sector[4] as proposed in the system described next.

3.1.2. Medium system

In this system we fixed the value for the energy-saving retrofit measures in the building sector to 50% of the 2010 value and the fraction of electric heat pumps in the heat sector to 75%. Furthermore we limited the potential of onshore wind facilities to 170 GW_{el} to create a more realistic system structure. The dimensioning of all other components is the subject of optimization.

The results illustrated in Fig. 3.4 show that the lower heat demand, due to the higher average extent of energy retrofit measures, leads to a significantly lower capacity of installed photovoltaic systems (205 GW_{el}). At the same time, the energy for heat in the building sector provided by gas-driven heat pumps decreases by about 50% (from 103 GW_{th} in the "REMax" system to 48 GW_{th} in this system configuration) whereas the installed capacity of electric heat pumps stays more or less constant.

Due to the lower installed capacity of photovoltaic systems, the oversupply peaks decrease and the capacity for power-to-gas facilities is reduced from 87 GW_{th} to 64 GW_{th}. Thus, less gas is produced (maximum stored amount of renewable gas: 62 TWh) and the advantage of using gas for space heating decreases. In addition, the lower heat demand leads to lower installed capacities of solar thermal systems (125 GW_{th} compared to 165 GW_{th} in the "REMax" system). This system leads to overall annual costs of about 115 billion €. The higher cost of the energy-saving retrofit measures in this scenario as compared to the "REMax" system is almost completely compensated by the decreased number of renewable energy converters and other conversion and storage components. An even higher decrease in the heat demand due to retrofit measures is investigated in the next paragraph.

3.1.3. RetrofitMax system

To consider the influence of further energy-saving retrofit measures on the system, the energy demand for heating is reduced to 40% of the value in 2010. In addition, the wind offshore capacity is limited to 75 GW_{el} to stay further away from the limiting technical potential. The dimensioning of all other components is the subject of optimization.

The stronger decrease in energy consumption for space heating causes an even stronger decrease in the installed capacity of photovoltaic systems (182 GW_{el}, cf. Fig. 3.5). At the same time, the installed capacity of gas-driven heat pumps reaches a value near zero. For decentralized heating, the only technological option used is the combination of electric heat pumps with solar thermal collectors. The rest of the energy needed for space heating is provided by the combined heat and power facilities in combination with central solar thermal collectors and large, centralized

[4] The influence of energy-saving measures in the electricity sector on the entire system has not yet been implemented in our model. Since electricity-saving measures can be implemented in very many applications at very different cost, it is impossible to define a single cost function to describe the cost of electricity saving.

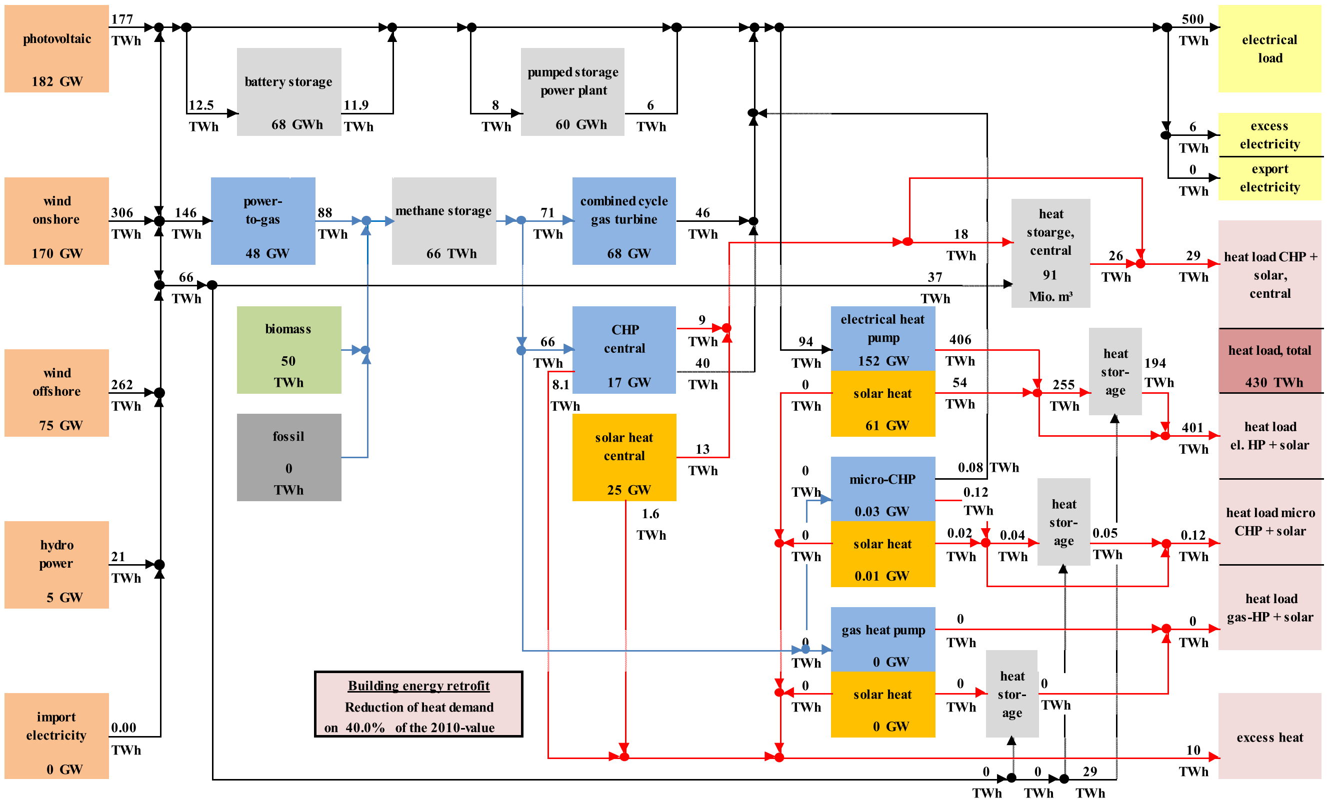

Fig. 3.5. "RetrofitMax" system.

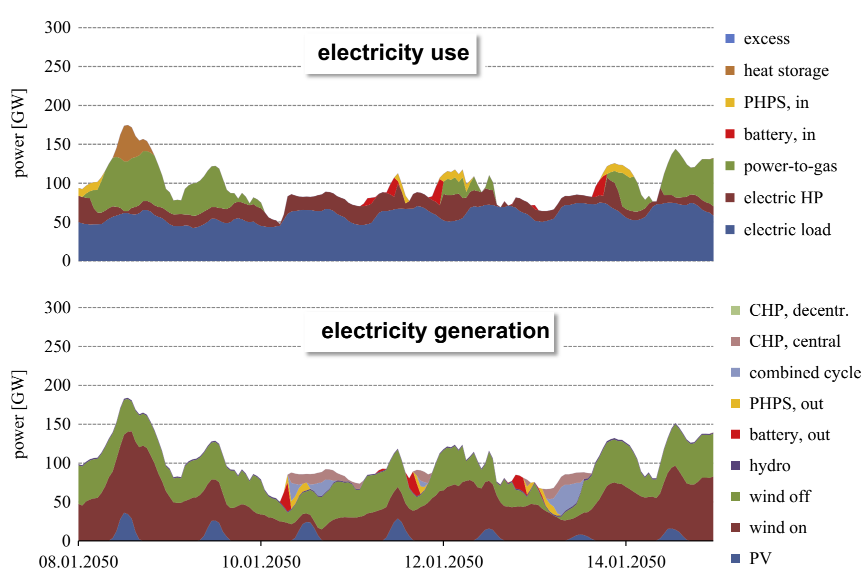

Fig. 3.6. Electricity generation and use of the "Medium" system during a winter week (CHP = combined heat and power; PHPS = pumped hydro-power storage; and HP = heat pump).

long-term heat storage. The installed capacity of power-to-gas is once again reduced from 64 GW_{el} in the "Medium" system to 48 GW_{el} in this system configuration.

The total system cost for this system is calculated to be about 120 billion € per year. The higher system cost is mainly caused by the cost for energy-saving building retrofit, which over-proportionally increases with increasing levels of implementation (cf. [1] and Section 4). The reduction in installed capacity of electricity-generating facilities, as mentioned in the previous paragraph, is not strong enough here to influence the total system costs positively. The reason is that the cost of energy-saving retrofit measures outweighs the cost savings gained by the smaller installed capacity of the other technologies.

It is noteworthy that the installed capacity of battery storage increases in this system configuration. One reason is the smaller amount of electricity produced by offshore wind turbines. This technology has the highest number of full load hours and thus acts as a kind of base-load power plant, causing the fluctuation in electricity generation to decrease. To compensate the daily fluctuation that is mainly caused by photovoltaic systems, the

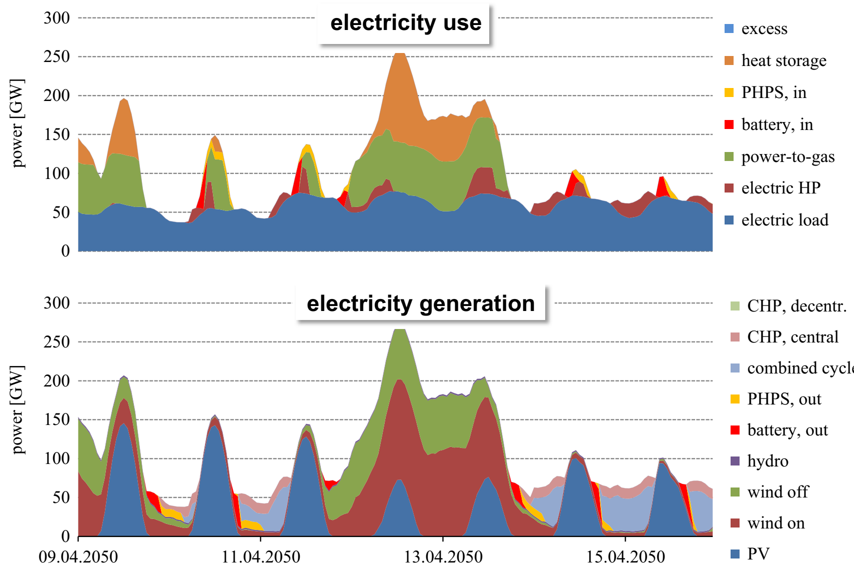

Fig. 3.7. Electricity generation and use of the "Medium" system during a spring week (CHP=combined heat and power; PHPS= pumped hydro-power storage; and HP=heat pump).

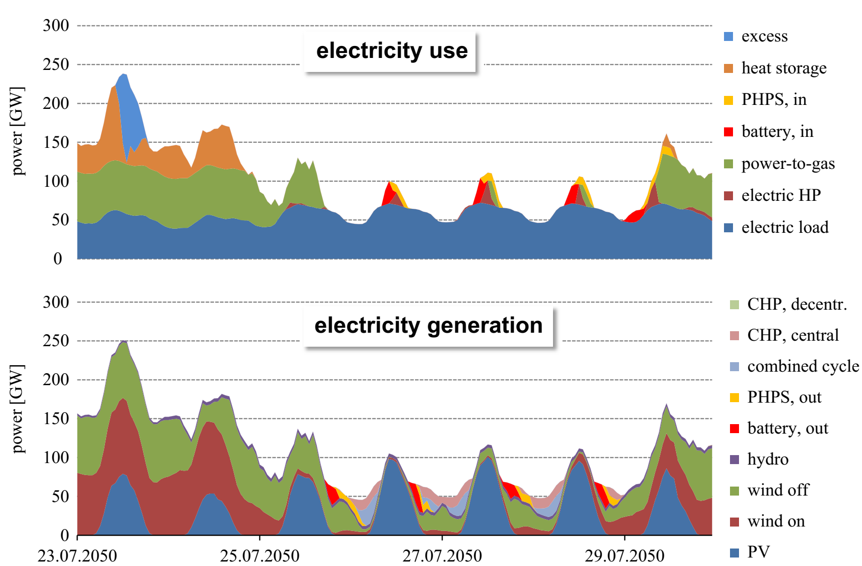

Fig. 3.8. Electricity generation and use of the "Medium" system during a summer week (CHP=combined heat and power; PHPS=pumped hydro-power storage; and HP=heat pump).

electricity storage capacity of batteries combined with photovoltaic systems has to increase.

Furthermore, it is conspicuous that in all three systems, small-scale decentralized CHP units (denoted micro-CHP in Figs. 3.1, 3.4 and 3.5) do not play any important role and reach values close to zero. There are two main reasons for this: firstly their high specific cost (1400 €/kW$_{el}$, see part I of this paper [1]) and secondly, the low process chain efficiency from electricity to gas and then to electricity and heat with CHP units. The electrical and thermal efficiency of the CHP units is small compared to the separately considered efficiencies of heat pumps and electricity generation in large-scale, combined-cycle power plants. We will investigate this system behavior in Section 4 in more detail.

All three systems have specific characteristics regarding the technical and economic structure. The "REMax" system was calculated with the total minimal system cost but results in high installed capacities of renewable energy converters, the "RetrofitMax" system has the lowest installed capacities due to extensive energy-saving retrofit measures but is the most expensive of the three and the "Medium" system lies somewhere between these two systems. Since the cost of the "Medium" energy system is only slightly higher than the least expensive system, we present the "Medium" system results in the following sections in more detail.

3.2. Hourly time series of electricity generation and use

This section presents analyses based on hourly time series of the "Medium" system for different weeks during the fictive year 2050. The aim is to analyze the system behavior in more detail and to better understand the interaction between the different technologies, and how production and demand is distributed between the implemented energy consumers, producers, transformers and storage units.

3.2.1. Winter

Fig. 3.6 shows the time series for electricity generation and use during a winter week. It can be seen that the electrical load as we define it, which is implemented using a base load and data taken from [8], plays the dominant role on the demand side of the electrical system. This load is defined to be the total electricity demand in Germany for all sectors including electricity for trains, industry and households but excluding electricity for space heating and hot water. The electricity needed directly for space heating and hot water is shown by the demand of the electric heat pumps.

At times of high wind velocities (here in particular at the beginning of the week), the electricity production from photovoltaic generators and onshore and offshore wind turbines exceeds the total electricity demand in the system. The surplus electricity is first stored in batteries and pumped hydro-power storage (PHPS) reservoirs, as long as these are not fully charged. Afterwards, the surplus electricity is used to generate renewable gas in the power-to-gas facilities. If the production capacity of these facilities is reached as well, the electricity is used for direct heating of the decentralized and central heat storage units (first day of the week shown).

During times with low generation of electricity from renewable resources (here the third and fifth days of the week), other electricity generators have to satisfy the demand. Fig. 3.6 indicates that first the available short-term storage types (batteries and PSPP) are discharged. If the available amount of electricity from these technologies is not sufficient, the combined cycle power plants (CCPP) and the combined heat and power plants (CHP) meet the gap in demand. If the renewable electricity generation rises again, the short-term storage units are recharged, so that short-term demand peaks occurring at a later point of time can be compensated again.

3.2.2. Spring

An example for the usage of surplus electricity is given by the time series shown in Fig. 3.7. During the daytime and especially in the middle of this week, the electricity production from photovoltaic generators and onshore and offshore wind turbines exceeds the demand in every hour. Hence, no further technology is needed at this time to balance the energy demand in the system. During the night, combined cycle and combined heat and power plants are the main suppliers.

The surplus electricity is handled as described in the previous paragraph. First the short-term storage units are charged, then renewable gas is generated and further surplus electricity is used for direct heating. The difference to the winter week shown before is that here the heat demand during the day is lower (abundant solar radiation, high ambient temperature) and thus the electric heat pumps have no direct need to operate. However, due to the implemented interaction of the electricity and heating sectors, the surplus electricity is used to charge the decentralized heat storage units more efficiently through the use of electric heat pumps. If the set-point temperature for electric heat pumps has been reached in the storage unit, it is heated further by the use of electric immersion heaters until the maximum permissible temperature has been reached. The charged heat storage units are now able to satisfy the heat demand during the night, when the ambient temperature decreases and the heating demand rises (hours without electricity from photovoltaics on the generation side and without demand from electric heat pumps on the “use” side).

3.2.3. Summer

The occasionally severe electricity surplus generated during summer, after initially charging the electrical and chemical storage units, is mainly used to charge the central seasonal heat storage units. This heat can later be used for heating through district heating grids, especially during winter. On the right side of the production peak in Fig. 3.8, it can be seen (on the first day of the week) that, after a certain time of charging, even the long-term seasonal heat storage units reach their maximum temperature and no further electricity can be stored as heat. This is one of the few moments during a year where the electricity generation has to be limited by transmission system operators (TSO). Over a whole year, only 5.2 TWh of excess electricity, which is less than 1% of the total electricity generated by wind, photovoltaic and hydroelectric power plants, has to be regulated and cannot be used. Admittedly

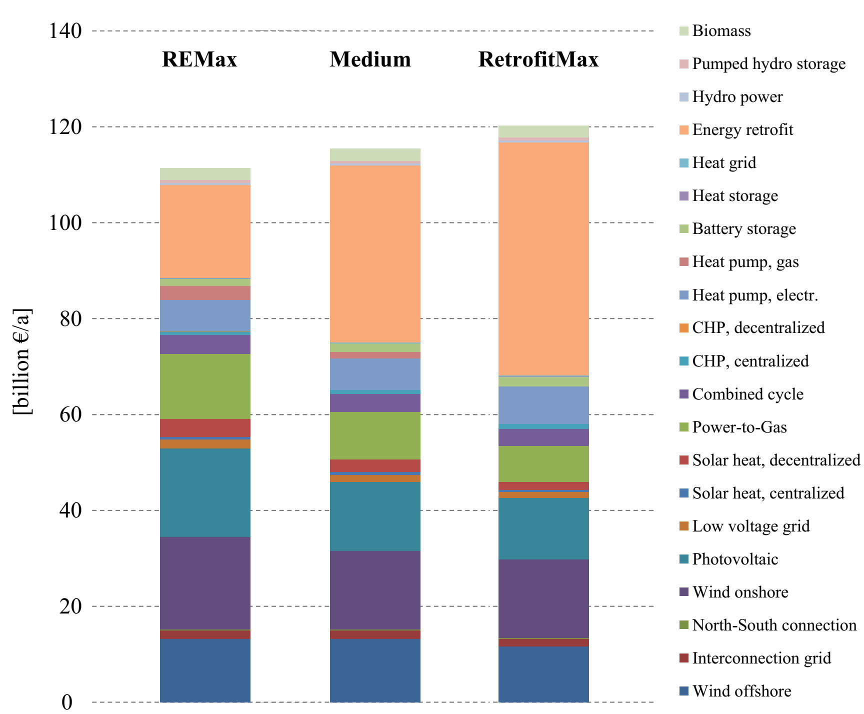

Fig. 3.9. Cost structure of “REMax”, “Medium” und “RetrofitMax” systems (CHP = combined heat and power).

at this stage, our model just examines the German infrastructure as a whole. This means that no restrictions concerning regional distances are implemented. Upon implementing these restrictions, the amount of electricity that has to be regulated will most likely rise.

The functioning of short-term electricity storage is illustrated nicely by the fourth, fifth and sixth days of this week. These days are characterized by almost no electricity generation from onshore wind and only a little electricity generation from offshore wind but exhibit pronounced generation of electricity by photovoltaic systems. During the daytime, first batteries and then pumped hydro-power reservoirs are charged and can almost completely use the surplus electricity. With reduced electricity generation by photovoltaic systems in the late afternoon, these storage units are then discharged before compensating electricity needs to be generated by combined cycle power plants and combined heat and power systems.

3.3. Cost analysis

The results from Section 3.1 indicate that different energy systems with different technological and cost structures can achieve a 100% renewable supply for heat and electricity and result in a total system cost between 111 and 120 billion € per year. The cost structure of the three previously discussed systems is shown in Fig. 3.9. Clearly noticeable is the large cost fraction for energy retrofit measures. Besides this component, the main cost fractions are for the electricity-producing facilities, photovoltaic, onshore and offshore wind and the combined-cycle gas turbines, the power-to-gas converters and electric heat pumps. The fact mentioned in Section 3.2, that the energy-saving retrofit measures reduce the high cost of the electricity-generating technologies, becomes particularly evident on comparing the “REMax” and the “RetrofitMax” cost composition. As the cost for energy retrofit measures increases, the cost for photovoltaic, wind onshore, gas-driven heat pumps, solar thermal collectors and power-to-gas facilities decreases almost proportionally. All other technologies listed in Fig. 3.9 increase the annual system cost, but their influence on the minimum system cost is significantly smaller than the large cost items of the main electricity and heat producers mentioned before.

In order to evaluate these numbers with regard to the current discussion about the German energy system, we try to estimate the cost of our current energy system based on fossil fuels. All end consumers in Germany paid about 260 billion € for the whole energy system in Germany in 2008 [9]. About half of this amount was the cost for energy sources that were imported (mainly fossil fuels) or were obtained within Germany (mainly brown and black coal). The other part consists of operation and maintenance costs for all necessary facilities (power plants, refineries, distribution and grids), financing costs for construction, reconstruction, taxes and charges, and the profits of the participating companies. Unfortunately there are no exact numbers attributed to each cost item. If we assume that about 50% of the second half mentioned consists of taxes and profits, then the maintenance and operation of the system, including the cost of energy resources, would cost about 194 billion €. As we only consider the electricity and heat sector, which corresponds to 62% of Germany's primary energy consumption, the proportional cost for the system fraction we investigate would be approximately 120 billion €. Therefore we can conclude that the investigated future energy system would have a cost similar to that of the system today, which is mainly based on fossil fuels.

Nevertheless, this conclusion is only valid for part of the energy supply system in Germany – namely the heat and electricity sector. In addition to that, it should be noted that the results are based on the cost assumptions we introduced in part I of this paper [1]. It is also important to note that we consider the total cost of a future energy system using renewable energy once the transition has been completed. This cost consists of investments needed to replace all included components once their lifetime has been reached, their operation and maintenance (O & M) cost and the cost for financing of investments. At the same time, it should be noted that the cost calculation for today's system does not include any external costs for CO_2 or other harmful emissions. The consideration of external cost for fossil or nuclear energy technologies would lead to significantly higher cost in today's system [10], whereas such external costs would not or at least not significantly appear in a completely renewable system like those presented in this paper. The world market price for today's sources of primary energy, mainly fossil fuels, has risen continuously in recent years. Fig. 3.10 shows the annual cost of today's (2008) energy system for the electricity and heat sectors for different rates of cost increase

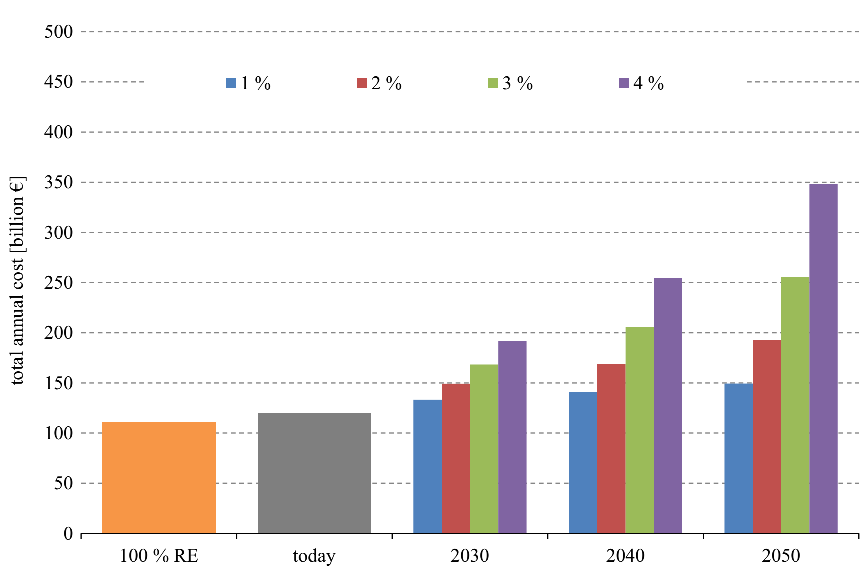

Fig. 3.10. Annual total cost of German energy system (considering only electricity and heat). On the left: energy system based on renewable energy. Second from the left: today's energy system. On the right: Cost of today's (2008) system with different rates of cost increase for primary energy in 2030, 2040 and 2050.

(without inflation) for the years 2030, 2040 and 2050, compared to the annual cost of a renewable system.

4. Sensitivity analysis and parameter studies

In this section we investigate certain parameters and their influence on the system in more detail. As decentralized CHP units do not play any important role with the parameters we introduced in [1], we will change their cost assumption and alter the assumed electrical and thermal efficiencies. In addition, we will investigate the influence of using fossil fuels, i.e. in a system with less than 100% renewable energy, and the influence of importing electricity in a European context. As Germany is unlikely to supply its electricity demand without import from other European countries, we assume that Germany has contracts with other countries and a certain amount of electricity is imported on an hourly basis. Furthermore we show the influence of different costs for energy-saving retrofit on the system composition and will investigate the effect on total system cost.

4.1. Small-scale decentralized CHP units

All scenarios shown in the previous chapter lead to negligible amounts of installed capacity for decentralized small-scale CHP units. To investigate the influence of the assumed price and efficiency on their impact in the 100% scenario, we vary the specific cost assumptions from 1400 €/kW$_{el}$ (initial value for an average small-scale CHP unit of about 20 kW$_{el}$, [1]) down to the very low value of 300 €/kW$_{el}$ in 100€ steps (see Fig. 4.1). In addition, we vary the electric efficiency, which was initially assumed to be 33% [1] up to an electric efficiency of 50% in steps of 1.5%. For CHP units of dimensions lower than 1 MW$_{el}$, a high value of 50% would only be realistic for units based on fuel cell technology.

The results show that the total cost minimum is not influenced by more favorable cost or technical performance assumptions for small CHP units. The installed capacity does not significantly change compared to the results shown in the scenarios (cf. chapter 3) discussed earlier. The calculated installed capacity stays below 1 GW and the total fraction of heat-generating facilities is hence still far below 0.1% of the total installed capacity.

Today, the use of CHP units in Germany is promoted by the government due to low natural gas prices, low specific CO_2 emissions and due to the comparably high total efficiency when electricity and heat are generated simultaneously. This is a reasonable measure as long as the produced heat can be fully utilized, i.e. at times with a high heat demand. However, this positive effect disappears when the system infrastructure, like the one introduced in this paper, strongly depends on flexible electricity generation in winter as well as in summer, when no heat can be utilized. From a systems perspective, the overall annual efficiency of small-scale CHP units drops due to the additional necessary utilization in summer when no heat is needed. However, in an energy system with a large contribution from fluctuating renewable energy sources (wind, PV), often more electricity is available than needed. This leads to a significantly reduced number of hours in which CHP units are able to generate heat and electricity simultaneously. Thus, the number of hours per annum with simultaneous operation and correspondingly high overall efficiency of CHP is strongly reduced and the required use of expensive synthetic gas in a future 100% renewable energy scenario penalizes CHP units in a cost-optimized system. Thus, cost optimization leads to very low installed capacities for CHP systems.

In order to investigate the influence of a forced increase in small-scale decentralized CHP units on the system infrastructure, we calculated two scenarios with a fixed value of 12 GW$_{el}$ and 24 GW$_{el}$ for decentralized CHP units (Fig. 4.2). The dimensioning of all other components was done as for the “Medium” system. In Fig. 4.2, we also include the previously discussed “Medium” system as a reference case. It can be seen that an increase in the capacity of decentralized CHP units causes the capacity of photovoltaics to increase significantly (260 GW$_{el}$ and 340 GW$_{el}$, respectively). This implies that the electricity needed for generating synthetic gas outweighs the fact that CHP units can generate electricity more flexibly. Thus, there is no positive effect on the sizing of renewable electricity-generating facilities by a larger volume of small-scale CHP units. To generate the larger amount of synthetic gas, more power-to-gas capacity is necessary (80 GW$_{el}$ and 100 GW$_{el}$, respectively). Hence, without any further advantage, the system has to be dimensioned larger and the total annual cost increases to 121 billion € and 129 billion €, respectively.

4.2. Fossil fuels and import of electricity

An energy system in which only renewable energy sources are used for heat and electricity is an extreme scenario. On the one hand, Germany is strongly integrated into the European energy system, especially concerning the electricity grid infrastructure that makes it possible to import and export electricity. On the other hand, fossil fuels will not disappear entirely until 2050 at the earliest. To assess the influence of these modified boundary conditions, we investigated scenarios with certain fractions of fossil fuels and scenarios including the influence of electricity imports on our model system.

4.2.1. Use of fossil fuels

Fig. 4.3 shows how the relevant system components change as a function of an increasing amount of fossil fuels in the system.

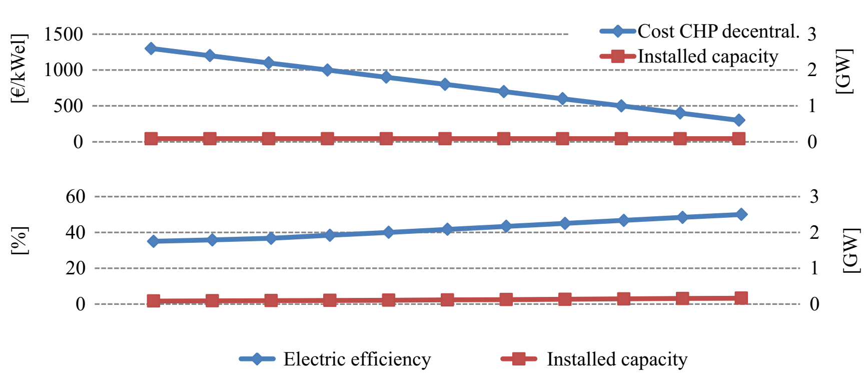

Fig. 4.1. Influence of lower costs (upper diagram) and higher electric efficiency (lower diagram) on the installed capacity of decentralized small CHP units. Each dot represents one varied parameter and the corresponding result.

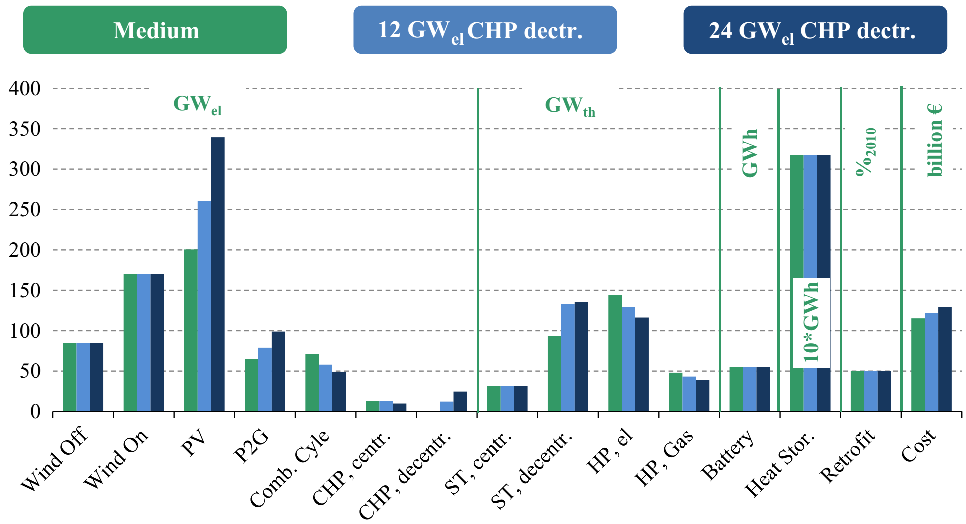

Fig. 4.2. Three different systems with different fixed values for the installed capacity of small decentralized CHP units.

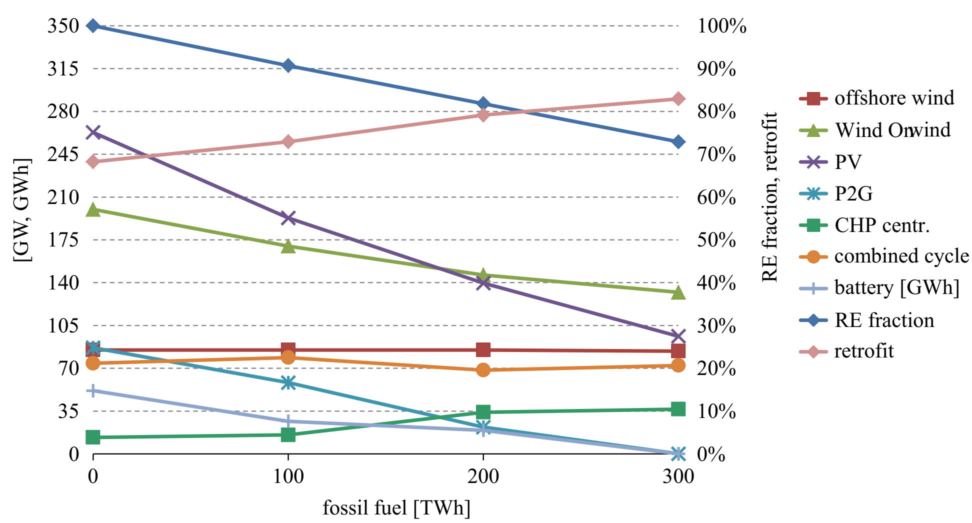

Fig. 4.3. Influence of different amounts of fossil fuels on the central elements of the energy system (offshore and onshore wind in GW, PV = photovoltaic in GW, P2G = power-to-gas in GW, CHP = combined heat and power in GW, combined cycle in GW, battery in GWh, RE fraction = renewable energy fraction in % and retrofit in %); the 100% scenario (i.e. 0 TWh of fossil fuel) corresponds to the "REMax" system.

We retained the structure of the overall system but simply assumed that in addition to the amount of gas available from biomass, a pre-defined amount of natural gas is available in the system. Thus, the fossil fuel can be used to generate electricity in the combined cycle power plants, in combined heat and electricity generation in CHP plants or to generate only heat in highly efficient gas-driven heat pumps. For each optimization, we fixed the amount of fossil fuels – 100 TWh, 200 TWh, 300 TWh – and calculated all other technologies as free parameters as described in chapter 3 or in detail in [1]. To put these numbers into perspective, 2000 TWh of fossil and nuclear energy was needed to supply the electricity and heat sectors in Germany in 2010 (cf. [2,3]). The results are shown in Fig. 4.3.

The following variables are shown in Fig. 4.3:

RE fraction This variable describes the ratio of energy from renewable energy sources to the total amount of energy consumed.

$RE\,fraction = \frac{E_{total} - E_{fossil}}{E_{total}}$

With this definition, we agglomerate all sources of energy, i.e. heat from solar thermal collectors, biomass, fossil fuels and electricity from renewable sources, with the same coefficient, i.e. we make no difference between electricity, gas and heat. The renewable energy fraction decreases nearly linearly from 100% when no fossil fuels are used to almost exactly 70% when 300 TWh of fossil fuels are assumed.

Offshore wind With 300 TWh of fossil energy in the system, the installation of offshore wind facilities reaches its technical potential. Consequently this is the cheapest and temporally best available technology to generate renewable electricity and its use is always given priority.

Onshore wind With 100 TWh of fossil energy, the fraction of onshore wind facilities has not yet reached its technical potential but 170 GW are still necessary. A larger amount of fossil energy causes the slope to reduce slightly and with 300 TWh in the system, the installed capacity of wind onshore facilities ends at 140 GW.

Photovoltaic The installed capacity of photovoltaics decreases from 262 GW at 100% renewable energy down to

	190 GW at 100 TWh fossil energy and even further to less than 100 GW when 300 TWh are used within the system.
Power-to-Gas	It is conspicuous that the required installed capacity for power-to-gas facilities steadily decreases with an increasing amount of fossil fuels. With 300 TWh fossil fuels in the system, there is no longer any need for renewable gas for long-term energy storage. The existing amounts of fossil fuels and biomass are sufficient to cover periods of insufficient availability of renewable energy, and only pumped hydro-power reservoirs and heat storage units are used to buffer the surplus electricity generation.
CC and CHP	It can be seen that the installed capacity of combined cycle power plants decreases constantly whereas the installed capacity for central CHP facilities increases to almost the same amount with increasing fractions of fossil fuels in the system. This behavior underlines the performance observed in the previous chapters. As long as fuel for CHP units is already available in the system, i.e. as long as gas does not need to be produced by renewable electricity, the use of CHP units is a reasonable option. In an entirely renewable energy system where all gas is produced by electricity, CHP units do not play an important role any more.
Retrofit	The higher the fraction of fossil fuels in the system, the lower is the demand for energy-saving retrofit measures in order to reach the cost-optimized system infrastructure. The annual demand for heat increases from about 68% in the 100% system to more than 80% when 300 TWh of fossil energy is used.

Especially the behavior of power-to-gas, energy-saving building retrofit and CHP facilities indicates how a transformation to a renewable energy system should be implemented in the coming decades. Only after the system reaches fossil fuel fractions that are below 30% does the need for gas-generating facilities increase and the advantage of CHP units diminish. Energy-conserving retrofitting in the building sector should start immediately and be continued throughout the entire energy system transformation towards an increasing share of renewable energy.

4.2.2. *Import of electricity*

Further calculations are made to investigate the influence of a possible import of electricity in a European context. To consider grid restrictions and thus to limit the hourly amount of imported electricity, we limit the total maximum power of transmission lines to neighboring countries. In the corresponding simulation runs, we assumed simply that electricity up to a certain power limit is imported if there is insufficient electricity from renewables, and that the combined cycle

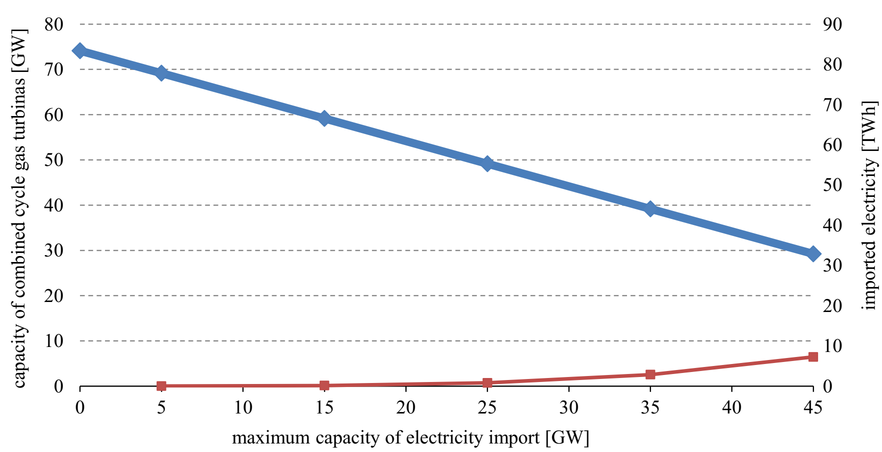

Fig. 4.4. Installed capacity of combined cycle gas turbines and annual amount of imported electricity versus the total maximum power of transmission lines to import electricity.

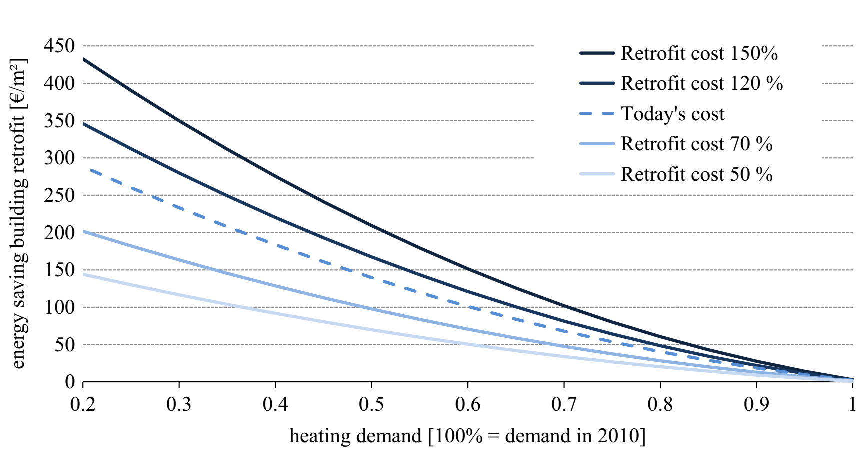

Fig. 4.5. Different energy-saving retrofit cost functions.

power plants are employed only when this limit is exceeded. The main effect of allowing electricity to be imported is that the installed capacity of combined cycle power plants can be reduced significantly. Fig. 4.4 shows how the increase of permitted capacity for transmission grids decreases the required capacity for combined cycle power plants.

In addition, it can be seen that the annual total amount of imported electricity is relatively low. Even with a large capacity of 45 GW_{el} of transmission lines to neighboring countries and a corresponding installed capacity of 30 GW_{el} of combined cycle power plants, only around 7 TWh of electricity are imported. This implies that most of the calculated installed capacity for combined cycle power plants is necessary to satisfy very short but high demand peaks.

As mentioned before, our model does not (yet) consider any effects of regional diversification of the energy system. Thus, the need for importing electricity in a more detailed system will possibly increase due to an increase of demand peaks in individual regions.

4.3. Energy-saving retrofit of the building stock

Energy-saving retrofit measures have a strong impact on the total cost and the system composition. Depending on the degree of retrofit, the selection of energy system components changes dramatically if the energy balance is to be achieved every hour of the year. The smaller the degree of energy-saving retrofit measures, the more renewable energy converters are needed to satisfy the higher heat and electricity demand. As mentioned in chapter 3, the "Medium" system turned out to be a reasonable scenario with the assumed cost functions introduced in part I of this paper (cf. [1]). Hence, we use this system as the basis for the following calculations.

First we investigated the influence of costs for energy-saving retrofit measures. The cost function introduced in part I of this paper is varied in two steps toward higher costs (150% and 120%, respectively) and lower cost (70% and 50%, respectively). Both scenarios are conceivable. On the one hand, the cost assumptions calculated from [11,12] that are valid for today could be too low because not all relevant buildings and their corresponding retrofit cost are covered correctly or an increase in the crude oil cost could increase the cost of the required insulation materials. On the other hand, high market penetration and standardized processes to produce the needed materials could decrease the cost in the next decades. The corresponding cost curves are shown in Fig. 4.5.

Fig. 4.6 shows the total annual cost for each cost function and system that is based on the "Medium" scenario. Depending on the assumed cost for energy-saving retrofit measures, the total annual system costs vary from 96 billion € to 134 billion €. It is noticeable that the system composition with the "Medium" system parameters does not change. This implies that there is no way to change the system into a less expensive system when the degree of energy-saving retrofit measures is fixed and the cost changes.

The main influence of energy-saving retrofit measures is determined by the degree of energy reduction. Depending on this degree, the system changes significantly due to a higher or lower energy demand that has to be satisfied by renewable energy sources. In Fig. 4.7 we calculated the whole system with all

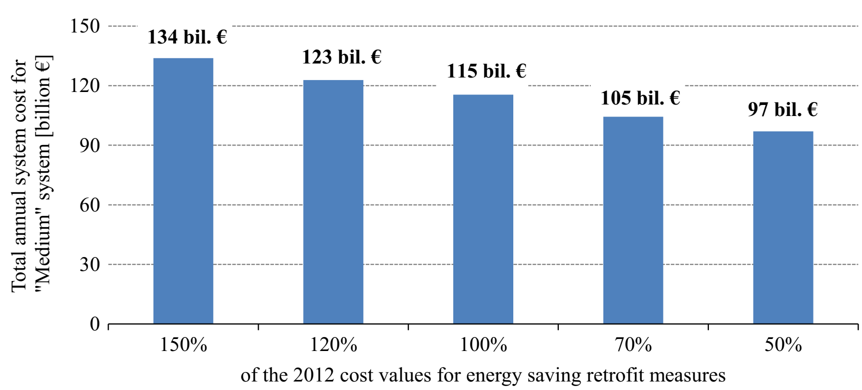

Fig. 4.6. Total annual cost for different energy-saving retrofit cost functions.

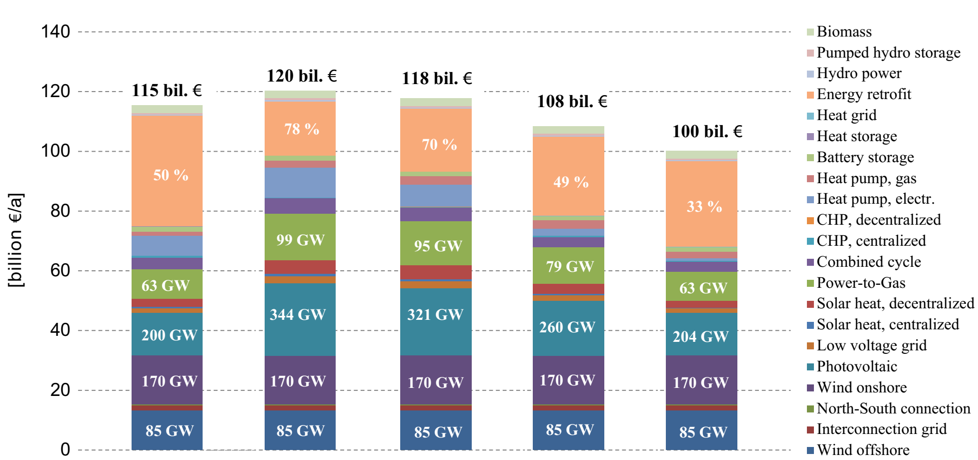

Fig. 4.7. Total annual cost composition for different energy-saving retrofit cost functions. The size of each color in a stack demonstrates the cost for each technology and the highlighted numbers indicate the installed capacity of each technology in GW or the degree of energy-saving retrofit measures as a percentage.

parameters free for optimization and an upper limit for onshore wind of 170 GW. It can be seen that the costs of energy-saving retrofit measures influence the degree of energy saving. With an assumed cost at 150% of today's cost (2012, cf. [1]), the reduction of energy for heating is only to 78% of the 2010 value. Nevertheless the total system cost, at 120 billion €, is comparably low. However, the installed capacity of photovoltaic is high at 344 GW_{el} and the size of power-to-gas facilities is also high at 99 GW_{el}. This is caused by the high energy demand from the building sector, where the energy consumption is only slightly reduced.

With a cost reduction down to just 50% of today's value, the installed capacity of the main cost components reaches a level comparable to the "Medium" system. Besides the onshore and offshore wind facilities, which reach the limit of technical potential in all calculations, photovoltaic and power-to-gas facilities reach values of 200 GW and 63 GW, respectively. The difference to the "Medium" scenario is found in the very high energy reduction in the building sector (down to 33%). This causes the heat demand to shrink to a minimum and the installed capacities of electrical and gas-driven heat pumps are reduced dramatically. In this calculation, the saved kWh of heating energy is cheaper than generating electricity or heat for the heating sector with renewable energy resources. Thus, reducing the energy demand in the building sector is the main leverage factor to reduce the total system energy demand.

We conclude that an ambitious level of energy-relevant retrofitting is needed in the building sector if the share of renewable energy used for the electricity and heating sector is to be close to 100% and the technical potential for their implementation cannot be fully exploited, for instance, for reasons of landscape conservation. This can be achieved either by reducing the cost for energy-saving retrofit measures or by policy measures such as subsidy programs or legal frameworks.

5. 100% renewable resources for all energy sectors?

The focus of our model is clearly restricted to the electricity and heating sector. We have not (yet) considered the influence of the energy demand caused by the fuel-based mobility sector and by fuel-based processes in the industry sector. In this section we will discuss why we neglected these sectors in a first step. Nevertheless, we try to assess the impact of including these sectors in the total energy system on an annual balance.

5.1. Fuel-based mobility

From our point of view, possible future technologies to replace today's combustion engines in this sector are: Battery-based electrical systems that are connected to and also charged from the regular electricity grid, vehicles that use hydrogen to generate electricity in fuel cells and different hybrid systems using a mix of these technologies. Recently, also concepts for trucks were discussed, which are based on an electricity supply infrastructure along highways (similar to train lines) which can be used by trucks that have electric motors [13]. From today's perspective, it is very difficult to assess which one of these, or even other technologies, will play a dominant role in the future mobility sector. Initial analyses of these systems suggest that battery-based systems are more likely to be used for short distances, i.e. within towns and cities. Hydrogen-based systems are better suited for long

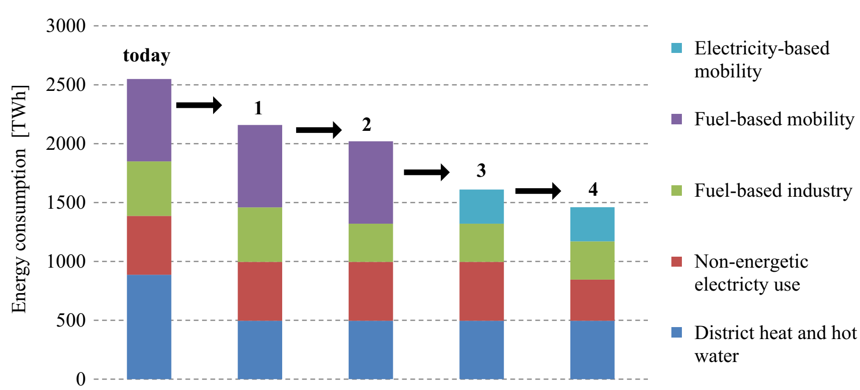

Fig. 5.1. Energy consumption and efficiency measures of different sectors to achieve a 100% renewable energy system for all sectors.

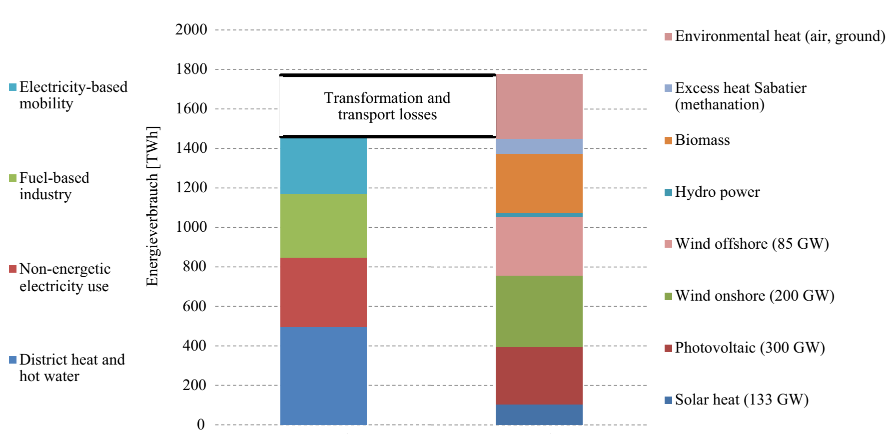

Fig. 5.2. Estimation of a future energy consumption to allow supply of all energy sectors of Germany with 100% renewable energy.

distances. However, all future technologies will use their energy in a much more effective way than vehicles applying internal combustion engines. The average conversion efficiency from fuel to kinetic energy of a modern combustion engine is less than 25% [14] whereas the efficiency of an electric engine is around 80% [15]. Therefore – assuming that the future driving behavior is similar to the situation in 2010 – the primary energy consumption for the future mobility sector will be significantly below today's values.

In future, our model will be extended so that different mobility scenarios can be calculated after the next step of development. Even now, we can make a rough estimate of a future energy demand from the mobility sector. Assuming that the driving behavior is constant and 50% of the vehicles run on hydrogen and the other 50% on batteries, an annual electricity demand of around 290 TWh will be necessary in comparison to 700 TWh [2] of fuel that is needed today[5].

5.2. Fuel-based industrial processes

Due to the great diversity of industrial processes, it is very difficult to generate hourly demand curves. This was the main reason why we have not (yet) implemented this demand in our model. The large variety of different temperature levels, for instance high-temperature processes in the chemical industry or low-temperature processes in the food industry, makes it very difficult to assess the hourly demand and especially the energy-saving potentials for all different kinds of industrial processes. However, as we implemented only a small amount (50 TWh) of the available biomass for use in the electricity and heat sector, there is still a large amount of biomass (solid, liquid, gaseous) available to be used as energy input for industry. In 2010, the total available energy from biomass in Germany was more than 300 TWh [2] so that at least 250 TWh is available for fuel-based processes in industry.

In a simplified way, Fig. 5.1 shows the required effort in energy-saving and reorganization measures to provide a 100% renewable energy supply for all energy-consuming sectors and simultaneously remain within the limits of the technical potential of renewable energy in Germany. The annual energy consumption of low-temperature heat, process heat, mobility and electricity for other purposes than as energy can fully be covered with renewable energy sources, as long as the conversion efficiency increases or the demand is reduced.

1. Decrease in heat demand for space heating of 50% compared to today's demand.
2. Decrease of fuel needed in the industrial sector by 30% compared to today.
3. Reorganization of the mobility sector with 50% of vehicles using hydrogen fuel cells and 50% of vehicles using battery systems.
4. Decrease of the electricity consumption (without electricity used for heat pumps) by 30% compared to today.

The total energy balance that leads to an energy system for Germany based on 100% renewables is shown in Fig. 5.2. To achieve this supply, all renewable energy potentials have to be used and in addition, the surplus heat from the power-to-gas facilities is used to replace fuels for process heat.

[5] The following conversion efficiencies were used to calculate these numbers: combustion engine 22%, electricity to hydrogen 70%; fuel cell 55%; battery + electric motor 85%.

It is noticeable that such a scenario has significantly lower conversion and transportation losses than the system that is implemented today. There are three main reasons: firstly, the large amount of electricity generated from renewable sources, secondly, the very high conversion efficiency of future combined cycle power plants and thirdly, the significantly lower conversion losses in the mobility sector.

6. Summary and outlook

With the results discussed in this paper, that were generated by the model introduced in the first part of this series of papers [1], we are able to optimize an energy system for an industrial country like Germany. Besides the cost-optimized results, which are based on detailed, hourly modeling of the interaction between electricity and heat, energy-saving retrofit measures for the building sector are also considered and their influence on the system can be studied in detail. With this novel model, we have created a link between the electricity and heat sectors to answer questions that are becoming increasingly important with rising fractions of renewable energy in industrial countries like Germany.

We found that the supply of the electricity and heat sectors in Germany with 100% renewable energy resources is technically possible and after the transformation of the energy system has been completed, the overall annual cost will be comparable to today's cost. This message is valid even though we assumed that the electricity demand will remain constant, that there is no electricity exchange with other countries, that today's costs for fossil fuels apply and that just a small amount of the available energy from biomass is utilized in these sectors. Also, we calculated the cost of today's energy system without including any external costs or hidden subsidies and without taking future increases in fossil fuel prices into account. A complete supply of the energy system under these conditions, however, is dependent on a high energy-efficiency standard of the building sector, whereby the energy demand for heating is reduced by 50% or more compared to the value in 2010. Therefore the costs for energy-saving retrofit measures represent a crucial value for the whole annual system cost.

Even with an energy demand for heating of buildings down to 50% of the 2010 value, the technical potentials of onshore and offshore wind facilities are utilized almost to the limiting values. Moreover, such an energy system is dependent on long-term storage capacity and on a certain amount of renewably produced gas to cover hours with little electricity generation from wind, photovoltaic and hydroelectric power plants. Solar power is used in both thermal collectors for space heating and hot water and in photovoltaic facilities to generate electricity. In the closely studied "Medium" system, the required installed capacity is around 200 GW_{el} (approx. 1250 Mio. m²) for photovoltaics and 130 GW_{th} (approx. 190 Mio. m²) for solar thermal collectors. More than three quarters of the necessary area is available on buildings and the rest can be installed on open areas or other sites as mentioned in Section 3 of this paper. The area needed for open space or alternative sites totals 400 km², which is an area of 20 km times 20 km. Decentralized CHP was shown to be comparably uneconomic. This is due to the lower conversion efficiencies from gas to heat and electricity compared to heat pumps and large-scale power plants, and the long conversion chain from electricity to gas and back from gas to heat and electricity. In addition, today's specific costs for small-scale CHP units are too high and even with very low assumed costs, no significant increase in installed capacity is found by the cost-optimization algorithm. Nevertheless, CHP units may be initially significant but their importance

decreases with decreasing fractions of fossil fuels in the energy system.

Additionally, we found that an energy system still based partly on fossil fuels, for instance with 70% of renewable energy technologies, needs much less installed wind and photovoltaic systems and especially much less power-to-gas converters for long-term storage reasons. These calculations indicated how a transformation to a renewable energy system should be implemented in the coming decades.

With the model introduced in part I of this paper [1], we have developed a powerful tool to assess different energy scenarios for national and regional energy systems in industrialized countries. At the same time, the model is able to assess the impact of specific technologies in a future renewable energy system. Sensitivity analyses can help to identify the performance and cost interdependence of different technologies in a future system infrastructure. For future work, several steps to develop the model are planned:

- Integration of energy demand from the fuel-based mobility and industrial sectors.
- Calculation of system transformation costs to assess the expenses for conversion of today's energy system to a system relying completely on renewable energy.
- A more detailed model of electricity exchange in a European context.
- Diversification of the model, especially for space heating demand, where the building structure in Germany will be characterized in greater detail.

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